

DISCOVERY OF A 3.6-HR ECLIPSING LUMINOUS X-RAY BINARY IN THE GALAXY NGC 4214

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Submitted to Astrophysical Journal

ABSTRACT

We report the discovery of an eclipsing X-ray binary with a 3.62-hr period within 24'' of the center of the dwarf starburst galaxy NGC 4214. The orbital period places interesting constraints on the nature of the binary, and allows for a few very different interpretations. The most likely possibility is that the source lies within NGC 4214 and has an X-ray luminosity, L_x , of up to 7×10^{38} ergs s⁻¹. In this case the binary may well be comprised of a naked He-burning donor star with a neutron-star accretor, though a stellar-mass black-hole accretor cannot be completely excluded. There is no obvious evidence for a strong stellar wind in the X-ray orbital light curve that would be expected from a massive He star; thus, the mass of the He star should be $\lesssim 3 - 4 M_\odot$. If correct, this would represent a new class of very luminous X-ray binary – perhaps related to Cyg X-3. Other less likely possibilities include a conventional low-mass X-ray binary that somehow manages to produce such a high X-ray luminosity and is apparently persistent over an interval of years; or a foreground AM Her binary of much lower luminosity that fortuitously lies in the direction of NGC 4214. Any model for this system must accommodate the lack of an optical counterpart down to a limiting magnitude of 22.6 in the visible.

Subject headings: galaxies: individual (NGC 4214) — galaxies: starburst — X-rays: binaries — binaries: general — binaries: eclipsing — stars: Wolf-Rayet

1. INTRODUCTION

With the advent of the sub-arcsec X-ray imaging capability of the *Chandra* X-ray Observatory (Weisskopf et al. 2003), observations of galaxies out to the Virgo Cluster routinely detect tens to hundreds of X-ray sources above detection limits of $\sim 10^{37 \pm 1}$ ergs s⁻¹ (Fabbiano & White 2006). In analogy with our own Milky Way, the majority of these bright sources are likely X-ray binaries. The precise nature of many of these objects is usually difficult to quantify because of a lack of high-quality X-ray spectra and light curves.

In a few instances, periodic dips are apparent in the observed X-ray light curves of individual sources. By interpreting these dips as eclipses by a companion star, the light curves can be used to constrain the system orbital parameters and even the mass of the compact object if suitable additional information is available such as an estimate of the companion star mass via spectral and luminosity-class typing (see, e.g., Weisskopf et al. 2004; Pietsch et al. 2004; Pooley & Rappaport 2005; Fabbiano et al. 2006).

NGC 4214 is a dwarf starburst galaxy, morphological type IAB(s)m, located 3.5 Mpc distant (1''=17 pc). The brightest X-ray source in NGC 4214, CXOU J121538.2+361921 (hereafter, CXOU J121538), shows distinct behavior indicative of an eclipse at a period of 3.62 hrs. This periodicity is visible in each of 5 X-ray observations taken over a 10-yr timespan though no more than two cycles are evident in any single observation. The X-ray light curves and spectra of the source are

presented in § 2. Upper limits from a search for an optical counterpart are given in § 3. An analysis of the X-ray source and its companion based on the observational evidence is derived in § 4. In § 5 we discuss the interpretation of the observations and the implications for the nature of the binary.

2. X-RAY TIMING AND SPECTRA

Table 1 lists the X-ray observations of NGC 4214 that include the variable source CXOU J121538. Previous analysis of the initial *Chandra* and the XMM-Newton observations are reported in Hartwell et al. (2004). They list source CXOU J121538 as source 11 at $\alpha = 12^h 15^m 38.^s 25$, $\delta = 36^\circ 19' 21.''4$ (J2000 coordinates). It is by far the brightest point source among the 20 discrete sources they detect, with a 0.3–8.0 keV flux of 3.0×10^{-13} ergs cm⁻² s⁻¹.

TABLE 1
X-ray observations of CXOU J121538.2+361921

Date of observation	Instrument	Exposure (ks)	Counts ^a (\pm error)
1994-12-10	ROSAT/HRI	42.6	91 \pm 12
2001-10-16	Chandra/ACIS-S	26.4	943 \pm 31
2001-11-22	XMM-Newton/PN	16.7	453 \pm 36
2004-04-03	Chandra/ACIS-S	27.2	201 \pm 16
2004-07-30	Chandra/ACIS-S	28.6	843 \pm 30

^abackground-subtracted in 0.5–8.0 keV energy band

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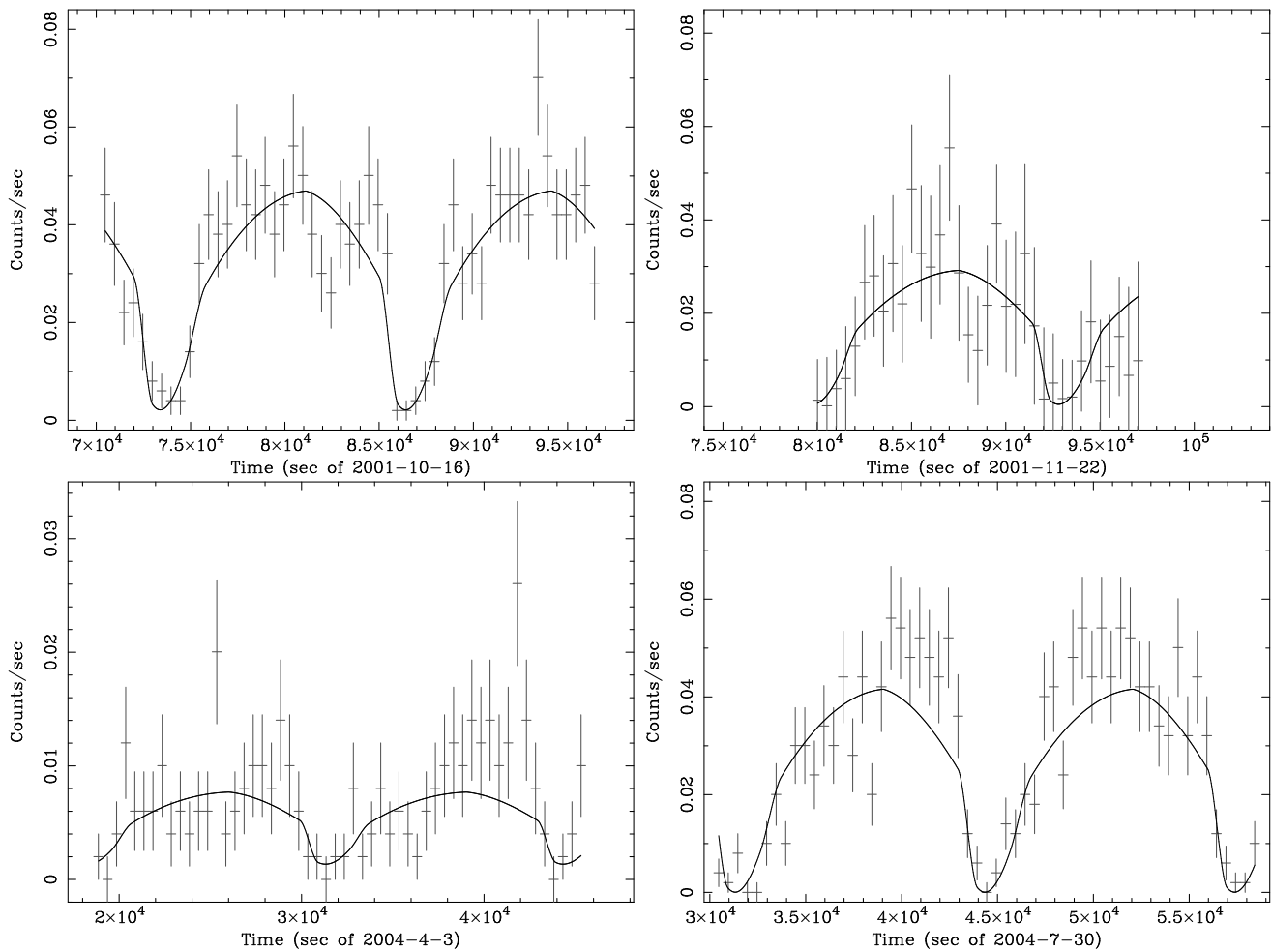


FIG. 1.— Background-subtracted *Chandra* and *XMM-Newton* X-ray light curves of CXOU J121538. The solid curve traces the best-fit 7-knot spline fit to the folded light curve (see text).

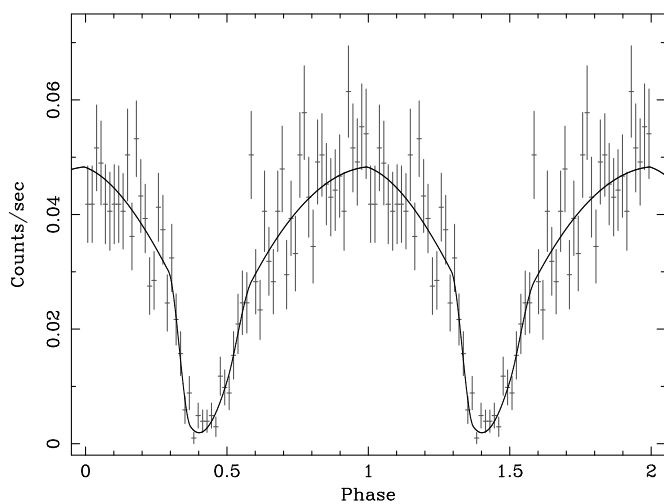


FIG. 2.— Folded light curve of the X-ray dataset made by combining the two brightest *Chandra* observations obtained on 2001-10-16 and 2004-7-30. The heavy curve denotes the best-fitting 7-knot spline model to this light curve.

Our locally-developed analysis software suite, **LExtrct** (Tennant 2006), was used to extract and analyze the source and background light curves and spectra from the

ROSAT and *Chandra* data. The *XMM-Newton* Science Analysis System (version is 6.5.0) was used for the *XMM-Newton* data. The nearest discrete source is $23.''7$ to the north and is only 10% of the flux of CXOU J121538. Thus, source CXOU J121538 is easily isolated from other discrete sources even in the *XMM-Newton* and *ROSAT* data. For the *Chandra* data, a circular extraction region of radius $5''$ was used for the source and a nearby region of area 170 square arcsecs was chosen for the background. For the *XMM-Newton* data, a circular source region of radius $15''$ and a background of 1385 square arcsecs were used for analysis.

The 0.5–8.0 keV *Chandra* and *XMM-Newton* light curves of CXOU J121538 are shown in Figure 1 (the *ROSAT* light curve is sparsely sampled because of the 90 min orbit of the satellite, and is not shown here). Prominent dips are seen in all four light curves. Using the longest exposure data, the *Chandra* observation on 2004-7-30, the light curve was folded on trial frequencies ranging from 6.4×10^{-5} to 1.2×10^{-4} Hz (some noise is apparent at lower frequencies). The resulting χ^2 statistic vs. trial frequency was fit to a Gaussian distribution. The peak of the Gaussian is at $7.682(60) \times 10^{-5}$ Hz corresponding to a period of 13020(100) s. A repeat of this procedure for the first *Chandra* dataset, from 2001-10-16, resulted in a

best-fit period of 12900(170) s.

Since both datasets have the same period, within the uncertainties, we combined them to increase the number of counts per phase bin. The minima of the two datasets were aligned via a χ^2 fitting procedure before they were added together. The folded light curve made from this combined dataset (in 64 phase bins, Fig. 2) was fit using a 7-knot spline with periodic boundary conditions to create a model light curve. This model was then applied to all the light curves as shown in Fig. 1. For these individual exposures, only the amplitude, phase, and DC level of the spline model were allowed to vary in the model fitting. A period of 13020(100) s is consistent with all the observations. However, since the uncertainty in the period is of order 1%, phase coherence is totally lost in 100 cycles or approximately two weeks; much shorter than the time between observations. For this analysis, no barycenter corrections were applied because they should be at most $\sim 30 \text{ km s}^{-1} \times 10^4 \text{ s}$ or about 1 lt-sec, which is well within our measurement errors.

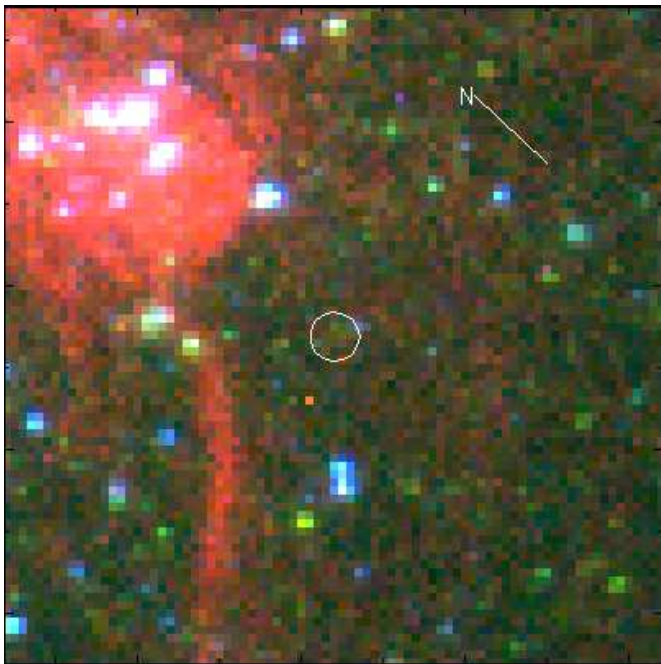


FIG. 3.— Three-color *Hubble* image of an $8'' \times 8''$ region around CXOU J121538 in NGC 4214. Data are from 1997 (MacKenty et al. 2000) and include F656N (red), F555W (green), and F336W (blue) filters. The error region for CXOU J121538, with a $1/3''$ radius, is shown as a circle near the image center. North is indicated.

Several models provide acceptable fits to the spectra of CXOU J121538 extracted from the individual *Chandra* and *XMM-Newton* observations. The model fit parameters are consistent with the values obtained by Hartwell et al. (2004); namely, for an absorbed power law model, $N_{\text{H}} = (1.8^{+0.6}_{-0.7}) \times 10^{21} \text{ cm}^{-2}$ and $\Gamma = 1.8^{+0.3}_{-0.2}$. The average flux in the 0.5–8.0 keV band ranges from $(2.0 \pm 0.1) \times 10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1}$ (on 2004-04-03) to $(3.41 \pm 0.34) \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}$ (on 2001-10-16). The flux during the bright phases on 2001-10-16 is $(4.77 \pm 0.48) \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}$. Fewer than 1000 source counts were accumulated during any individual X-ray observation of CXOU J121538 (Table 1). Therefore, no other important constraints on the nature of the source can be deduced from these spectra.

If the dips in the light curve are due to an eclipse, then the spectral shape during time intervals near the minimum in the light curve may differ from the shape at other times due to changes in absorption or scattering of X-rays by the atmosphere or wind of the companion star. To test for this possibility, we compared spectra extracted from high- ($>0.035 \text{ c s}^{-1}$) and low-count-rate ($<0.025 \text{ c s}^{-1}$) phases of the 2001-10-16 *Chandra* observation. A Kolmogorov-Smirnoff test showed these spectra are consistent with being drawn from the same parent distribution at the 40% level. Examination of the soft (0.5–2.0) and hard (2.0–8.0 keV) light curves also show no evidence for enhanced absorption near or away from eclipse.

In summary, periodicity is apparent in all the observations of CXOU J121538. We surmise the periodicity is due to an eclipse of the X-ray source by a companion star and that the orbital period of the system is $P_{\text{orb}} = 13020(100) \text{ s} = 3.62(3) \text{ h}$.

3. OPTICAL COUNTERPART SEARCH

Hubble observations of NGC 4214 were carried out in 1997 in several filters as reported by MacKenty et al. (2000). The dynamical center of NGC 4214 (*Chandra* source 10 in Hartwell et al. 2004) and CXOU J121538 are both located on the WPC2 camera 3 in these observations making the registration between the optical and X-ray images accurate. We estimate the radius of the X-ray error circle to be $\sim 0.3''$. There are several optical sources within this circle in the *Hubble* images (Figure 3). Taking the total light within the error circle as a conservative upper limit to any potential counterpart, we deduce the following observed magnitudes: $m_{\text{F336W}} = 23.6 \text{ mag}$, $m_{\text{F555W}} = 23.7 \text{ mag}$, $m_{\text{F702W}} = 22.4 \text{ mag}$, and $m_{\text{F814W}} = 22.0 \text{ mag}$. Since the different sources within the error circle contribute different amounts in the different bandpasses, optical colors based on the total light are not meaningful. An estimated reddening correction can be made from the fitted X-ray absorption column, which averages to $\sim 2 \times 10^{21} \text{ cm}^{-2}$, corresponding to $A(V) \sim 1.1 \text{ mag}$. The resulting upper limit to the optical counterpart to CXOU J121538 is $m_{\text{F555W}} = 22.6 \text{ mag}$. By way of comparison, we note that this is about equivalent to a late OV star at the distance of NGC 4214.

4. ORBITAL CONSTRAINTS

4.1. Orbital Period

In order to understand what this eclipse discovery implies, we start by examining the constraints on the donor star set by the measured orbital period, $P_{\text{orb}} = 3.62 \text{ hr}$. First we take Kepler's 3rd law:

$$\frac{GM_T}{a^3} = \left(\frac{2\pi}{P_{\text{orb}}} \right)^2, \quad (1)$$

where M_T and a are the total binary mass and orbital separation, respectively, and utilize the relation: $R_L = r_L a = R_{\text{don}}/f$, where R_L is the Roche-lobe radius of the donor and f is the fraction of the Roche lobe that is filled by the donor star of radius R_{don} . Combining these, we find:

$$\frac{R_{\text{don}}^{3/2}}{f^{3/2} M_T^{1/2} r_L^{3/2}} \simeq 0.36 \left(\frac{P_{\text{orb}}}{1 \text{ hr}} \right), \quad (2)$$

where M_T and R_{don} are in solar units. Finally, we make use of Eggleton's (1983) expression for r_L to find:

$$\frac{R_{\text{don}}^{3/2}}{M_{\text{don}}^{1/2}} \simeq 0.12 \xi(q) f^{3/2} \left(\frac{P_{\text{orb}}}{1 \text{ hr}} \right), \quad (3)$$

where

$$\xi(q) \equiv \frac{q^{1/2} \sqrt{1+q}}{[0.6q^{2/3} + \ln(1+q^{1/3})]^{3/2}}, \quad (4)$$

and q is the mass ratio $M_{\text{don}}/M_{\text{acc}}$. Here, M_{acc} is the mass of the accreting star. Equation (3) is analogous to the classical radius-mass relation (e.g., eq. [3] of Pooley & Rappaport 2005; see also the discussion in Weisskopf et al. 2004) for Roche-lobe filling donor stars, but is generalized via Eggleton's (1983) expression for r_L for virtually any mass ratio. The function $\xi(q)$ differs by less than 10% from unity for $0.01 \lesssim q \lesssim 2$, and increases to a value of only 1.35 as $q \rightarrow 10$. An additional feature of eq. (3) is that the factor f allows for donor stars that underfill their Roche lobes.

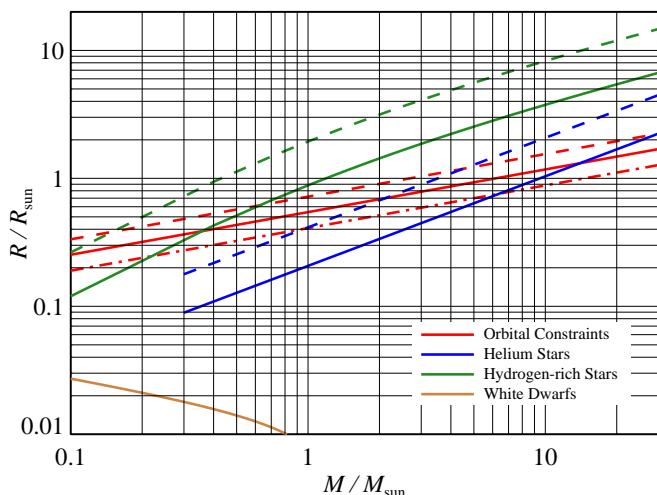


FIG. 4.— Constraints on the eclipsing source CXOU J121538 in NGC 4214. Red curves: radius-mass constraints set by the value of P_{orb} ; solid, dashed and dot-dashed curves correspond to the mass ratio, $q \equiv M_{\text{don}}/M_{\text{acc}}$, and Roche-lobe filling parameter, f , in the following pairs (1,1), (10,1) and (1,3/4), respectively. Green curves: H-burning stars; solid (dashed) curve represents the zero (terminal) age main sequence. Blue curves: He-burning stars; solid (dashed) curve represents the zero (approximate terminal) age main sequence. Orange curve: degenerate (He) dwarfs.

A plot of eq. (3), with $P_{\text{orb}} = 3.62$ hr, is shown in Figure 4 in the radius-mass plane of the donor star. The solid (dashed) red curve is for all $q \lesssim 2$ ($q = 10$); both curves are for $f = 1$ (i.e., a Roche-lobe filling donor). The lower red dot-dashed curve represents the case where the donor star fills only 3/4 of its Roche lobe, and $q = 1$. The solid (dashed) green curve is a simple $R(M)$ relation for zero age (terminal age) H-burning main-sequence stars, while the solid (dashed) blue curve is the $R(M)$ relation for zero age (terminal age) He-burning main-sequence stars (see, e.g., Paczyński 1971; Kato & Iben 1992; Justham & Podsiadlowski 2006, private communication). For completeness, we show, as an orange curve, the $R(M)$ relation for degenerate He stars.

From an inspection of Figure 4, and the intersection of the red curves with the green and blue curves, we can draw some basic conclusions about the nature of the donor star.

Hydrogen-burning companion star

One obvious interpretation of the nature of the eclipsing binary is a normal main-sequence donor star with a mass of $\sim 0.4 M_{\odot}$ (the intersection of the green and red curves of Figure 4). This, coupled with an orbital period of 3.62 hr, evokes either a conventional low-mass X-ray binary (LMXB) in NGC 4214, or a cataclysmic variable binary (CV) with a white dwarf accretor in our own Galaxy. In the former case, an important question would be how an unevolved, low-mass donor star could drive a sufficiently high rate of mass transfer to account for $L_x \simeq 7 \times 10^{38}$ ergs s $^{-1}$. Mass transfer from an unevolved $0.4 M_{\odot}$ star is induced by orbital decay through gravitational radiation and magnetic braking (see, e.g., Rappaport, Verbunt, & Joss 1983). The mass transfer rate would then be low and we estimate the corresponding X-ray luminosity would range from only $\sim 2 \times 10^{36}$ ergs s $^{-1}$ (for gravitational radiation and a neutron star accretor) to $\sim 6 \times 10^{37}$ ergs s $^{-1}$ (for magnetic braking and a stellar-mass black hole accretor).

In the case that CXOU J121538 is a CV in our own Galaxy, the shape of the X-ray eclipse (see, Figs. 1 and 2) is reminiscent of that of AM Her systems (Heise et al. 1985). If CVs are confined to the Galactic disk with a scale height $H \sim 300$ pc, then CXOU J121538, in this interpretation, would be within ~ 1 kpc, corresponding to an X-ray luminosity of $\sim 6 \times 10^{31}$ ergs s $^{-1}$, or about 1/3 of the average luminosity for AM Her systems (see, e.g., Ramsay & Cropper 2003).

There are no physical solutions for extremely – or even moderately – evolved normal main-sequence stars which would more naturally drive the high rate of mass transfer implied for a system at the distance of NGC 4214.

Helium-burning companion star

Another obvious possibility for the nature of the binary is a He-burning star in a binary with either a neutron-star or stellar-mass black-hole accretor (see also Weisskopf et al. 2004). The intersection of the various orbital constraint (red) curves with the He-star (blue) curves in Fig. 4 yield a range of possible combinations of He-star mass and accretor mass. For example, a $\sim 12 M_{\odot}$ He-ZAMS star could fill its Roche lobe with an accretor of comparable mass (i.e., $q \sim 1$), e.g., a $\sim 12 M_{\odot}$ black hole. Alternatively, a more massive He-ZAMS donor of $\sim 23 M_{\odot}$ would fill its Roche lobe with a much less massive accretor, e.g., a neutron star. Or a $\sim 7 M_{\odot}$ He-ZAMS donor could underfill its Roche lobe (by a factor of, e.g., 3/4) and still achieve substantial mass transfer via a stellar wind. However, for reasons discussed below, perhaps the most promising interpretation is an intermediate-mass He star (e.g., $\sim 2-3 M_{\odot}$) that is somewhat evolved, with approximately twice its main-sequence radius, or near the He terminal-age main sequence (TAMS).

4.2. Eclipse Duration

For the case where the X-ray eclipse is due to the compact accretor going behind the companion star, we can

also use the eclipse duration to learn more about the constituent masses of the binary. Note that these constraints would therefore pertain to the case of the He-star companion, but probably not to an AM Her-type eclipse. We modify the expression for the eclipse half angle, θ_{ecl} , from eq. (4) of Pooley & Rappaport (2005; see also Weisskopf et al. 2004) to allow for arbitrary mass ratios, q :

$$\theta_{\text{ecl}} = \cos^{-1} \left[\frac{1}{\sin i} \sqrt{1 - r_L^2} \right], \quad (5)$$

where i is the orbital inclination angle, and

$$r_L = \frac{0.49q^{2/3}}{[0.6q^{2/3} + \ln(1 + q^{1/3})]}, \quad (6)$$

(Eggleton 1983). A plot of $\theta_{\text{ecl}}(q)$ is shown in Fig. 5 for inclination angles of 90° , 80° , and 70° . The horizontal lines denote our estimates for the maximum and minimum observed eclipse half angles. We have not performed any detailed eclipse calculations for the case where a stellar wind accounts for an appreciable portion of the X-ray modulation. Given the limited statistical precision associated with the X-ray light curves, we can say only that the drop in intensity more closely resembles a classical X-ray eclipse, i.e., as in a high-mass X-ray binary, than a wind-modulated light curve, e.g., X1908+075 (Levine et al. 2004).

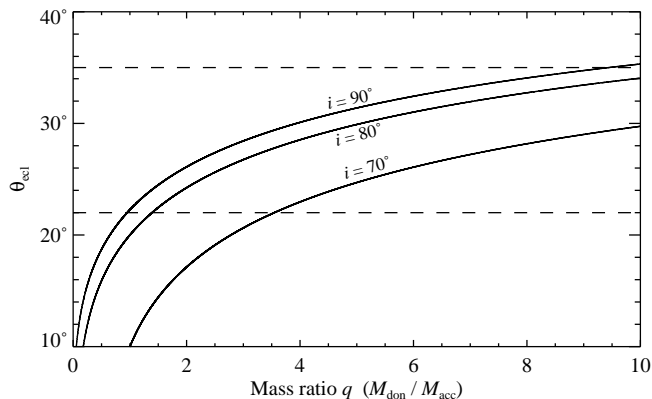


FIG. 5.— Geometric eclipse half-angle (in degrees) as a function of the mass ratio, for several values of the inclination angle, i (eq. [5]). The horizontal lines are estimates for the observed upper and lower limits on θ_{ecl} .

From the intersection of the two horizontal curves with the $\theta_{\text{ecl}}(q)$ curves in Fig. 5, we conclude that the mass ratio in this system is

$$1 \lesssim q \lesssim 10. \quad (7)$$

This range of q values is consistent with the illustrative system components suggested above. In particular, unevolved He stars of mass $\sim 7 - 18 M_\odot$ could have a black-hole accretor of $\sim 7 - 12 M_\odot$ (intersection of solid blue with solid and dot-dashed red curves in Fig. 4). Higher mass He stars (i.e., $\gtrsim 22 M_\odot$) would require much less massive accretors (e.g., neutron stars; intersection of solid blue and dashed red curves). Finally, somewhat evolved He stars of $\sim 2 - 3 M_\odot$ could have neutron-star or very low-mass black hole accretors.

5. DISCUSSION

Our observations of a 3.62-hr eclipse in the source CXOU J121538 have yielded three distinct possibilities for the nature of the binary. We discuss the pros and cons of each in turn.

5.1. Conventional LMXB

As discussed above, in the context of the orbital constraints, if the donor is a H-rich, low-mass star it cannot be very evolved. Thus, it is unclear how an unevolved, low-mass donor star could drive a sufficiently high rate of mass transfer to account for values of L_x that approach $7 \times 10^{38} \text{ ergs s}^{-1}$ during several different observations spanning nearly 3 years – especially if the accretor were a neutron star. Conventional black hole LMXBs, on the other hand, can have high luminosities but only during short transient outbursts. Systems with short orbital periods like CXOU J121538 should either not be transients or, if they are, should not have such prolonged intervals of high \dot{M} (see, e.g., King et al. 1996; Kalogera et al. 2004; Fabiano et al. 2006). Moreover, if the accretor were a stellar-mass black hole then $q \ll 1$ and the eclipse duration would be much shorter than observed (Figure 5).

In discussing a possible short orbital period ULX, Liu et al. (2002) suggested beaming of the X-radiation to reduce the actual value of L_x . Given that CXOU J121538 is an eclipsing system this possibility seems remote, though not impossible if the accretor were a rapidly spinning black hole, and a large kick during its formation oriented the orbital plane perpendicular to the spin axis.

5.2. CV/AM Her system

For the case of an AM Her system, the eclipse would be caused by periodic occultations of the accreting magnetic polar cap as it rotates around the spin axis of the white dwarf. In this case, we cannot infer anything further about the mass ratio of the binary constituents, as in Fig. 5. Thus, we focus here on the constraints set by the HST image (Fig. 3), and an evaluation of the probability of finding a high Galactic latitude ($b \simeq 78^\circ$) AM Her binary within the D_{25} area of NGC 4214. As discussed in §3, the limiting visual magnitude for any counterpart to CXOU J121538 is 22.6. However, at $P_{\text{orb}} \simeq 3.62 \text{ hr}$, we expect the donor star in an AM Her system to be roughly of intrinsic spectral type $M0 V - M3 V$ with visual magnitude $8.9 \lesssim M_V \lesssim 10.5$. From the optical limit, this requires the source to be at least 2.6 to 5.5 kpc away. Thus, unless the hypothesized AM Her system is in the Galactic halo, the observed constraint on its magnitude seems difficult to reconcile with its expected brightness.

It also seems somewhat unusual that an AM Her system would be found by chance so close ($\sim 25''$) to a particular galaxy that is being observed with *Chandra* for the purpose of detecting luminous X-ray sources. The D_{25} ellipse region associated with NGC 4214 has semi-minor and semi-major axes of $197''$ and $255''$, respectively. This corresponds to a solid angle of ~ 44 square arcmin, or 0.012 square degrees. If there are n_{CV} CVs pc^{-3} with $P_{\text{orb}} \gtrsim 3 \text{ hr}$, then the surface density, S , toward the NGP is $2n_{\text{CV}}H^3 \text{ sr}^{-1}$, for an assumed exponential distribution of CVs from the Galactic plane with scale height H . For illustrative parameters of $n_{\text{CV}} \sim 10^{-6} \text{ pc}^{-3}$ (see, e.g., from

observations, Patterson 1984; Howell et al. 2002; Schmidt et al. 2005; Gansicke et al. 2005; Szkody et al. 2006; and from population models, de Kool 1992; Kolb 1993; Han et al. 1995; and Politano, Howell, & Rappaport 1998) and $H \sim 300$ pc, we have $S \sim 55$ per steradian, or ~ 0.016 per square degree. Thus, the a priori probability of finding a CV with $P_{\text{orb}} \gtrsim 3$ hr within the 0.012 square degree area of the NGC 4214 D_{25} ellipse seems quite small, i.e., $\sim 2 \times 10^{-4}$.

Finally, in regard to finding a CV close to a galaxy of particular interest, we note that a similar circumstance has arisen in the case of CG X-1 in the field of the Circinus galaxy (Weisskopf et al. 2004). This particular eclipsing source had an orbital period of 7.5 hr, which already is quite long for an AM Her system. The Circinus galaxy is at $b \simeq -3.8^\circ$ (compared to 78° for CXOU J121538), and therefore the probability of finding a chance foreground CV is higher than near the NGP. Nonetheless, these two eclipsing sources, when taken together, reduce the likelihood that both are foreground CVs.

Overall, we find the hypothesis that CXOU J121538 is a foreground AM Her system to be implausible.

5.3. Naked He-burning donor star

If we interpret the CXOU J121538 system as having a naked He-burning donor star of mass somewhere in the range of $\sim 2 - 20 M_\odot$, the requisite mass-transfer rate, \dot{M} , could be achievable via either direct Roche-lobe overflow or via Bondi-Hoyle capture (see, e.g., Bondi & Hoyle 1944) of a modest fraction of the stellar wind from the He star (Dewi et al. 2002; Justham et al. 2006). For the lower-mass He stars within this range, direct Roche-lobe overflow would probably be required to supply the mass transfer rate. The nuclear lifetimes of He stars in this mass range are quite short ($\sim 3 \times 10^5$ to 3×10^6 yr; Paczyński 1971; Habets 1986; Langer 1989; Kato & Iben 1992; Dewi et al. 2002; Justham & Podsiadlowski 2006, private communication) so that \dot{M} values of $\gtrsim 10^{-7} M_\odot \text{ yr}^{-1}$ are easily attained.

If the donor star is indeed a He-burning star, there is an additional constraint that the X-ray light curve neither appears to be dominated by modulation in a dense stellar wind, nor suffers from any obvious photoelectric (i.e., strongly energy-dependent) absorption. For a simple $1/r^2$ stellar wind profile, the column density as a function of orbital phase (at $i = 90^\circ$) has a simple analytic form:

$$N = n_0 a \phi / \sin \phi \quad , \quad (8)$$

except for values of ϕ corresponding to direct geometric eclipse (e.g., Levine et al. 2004), where n_0 is the wind density at the orbit of the compact accretor, a is the orbital radius, and ϕ is the phase angle (with $\phi = 180^\circ$ being defined as superior conjunction). For some illustrative parameters, we find:

$$N \simeq 10^{23} \dot{M}_{-6} \left(\frac{a}{3 R_\odot} \right)^{-1} v_{1000}^{-1} \text{ cm}^{-2} \quad , \quad (9)$$

where the units for \dot{M} and v are $10^{-6} M_\odot \text{ yr}^{-1}$ and 1000 km s^{-1} , respectively. Thus, unless the stellar wind is essentially completely ionized, the optical depth to soft X-rays would be enormous. For stellar-wind density profiles that

start with zero velocity and infinite density at the stellar surface (e.g., Lucy & Solomon 1970; Castor, Abbott, & Klein 1975), the column densities would be larger, and the discrepancy with the observed light curve would be even greater. Therefore, if the donor star in CXOU J121538 is ultimately identified with a He star with $M \gtrsim 3 - 4 M_\odot$, this apparent lack of a dense stellar wind will have to be reconciled with the binary stellar model.

To quantify the constraint on the He-donor star set by the apparent lack of a strong stellar wind, we utilize the following expression for stellar-wind rates as a function of luminosity by Hamann, Koesterke, & Wessolowski (1995):

$$\log \dot{M} (M_\odot \text{ yr}^{-1}) = -11.95 + 1.5 \log (L/L_\odot) \quad , \quad (10)$$

where L is the bolometric luminosity of the He star. More recently, Hamann & Koesterke (1998) and Petrovic, Langer & van der Hucht (2005) have suggested that the wind loss rates are lower than given by eq. (10) by factors of a few. Only for luminosities $\lesssim 10^4 L_\odot$ does the donor star avoid producing a highly attenuating stellar wind (e.g., with $\dot{M} \lesssim 10^{-6} M_\odot \text{ yr}^{-1}$). This luminosity, in turn corresponds to He star masses $\lesssim 3.5 M_\odot$ (Kato & Iben 1992; Justham & Podsiadlowski 2006, private communication). Our limit on the optical counterpart of 22.6 magnitudes, is also much more consistent with lower mass He stars (i.e., $2 - 3 M_\odot$).

6. SUMMARY AND CONCLUSIONS

The brightest X-ray source in the field of the galaxy NGC 4214, CXOU J121538.2+361921, shows distinct eclipse-like intensity dips at a period of 3.62 hr. These eclipses are present in each of five X-ray observations spanning 1994 to 2004. Assuming that these eclipses are indicative of the orbital period, we can rather tightly constrain the nature of the binary system.

We have considered the possibility that CXOU J121538 is a conventional LMXB that somehow produces a very high luminosity for a sustained interval of time. The mass transfer rate that can be driven by a low-mass, unevolved donor star is too low to supply the requisite mass transfer rate, and it is unlikely that this source is, or should be, a transient.

We have also evaluated quantitatively the possibility that the CXOU J121538 system is a foreground CV (of the AM Her subtype). Major difficulties with this scenario are (i) the improbability of finding an AM Her system aligned so closely, by chance, with a galaxy of interest (even after taking into account the fact that *Chandra* has observed a substantial number of such galaxies with equal exposure), and (ii) the lack of an optical counterpart brighter than 22.6 mag, requiring the CV be a halo object. We consider this possibility unlikely.

The alternative is that the donor is a He-burning star. He-donor star masses $M \gtrsim 4 M_\odot$ are difficult to reconcile with the apparent lack of a dense stellar wind. We believe that the most likely interpretation of this system is a $\sim 2 - 3 M_\odot$ slightly evolved (e.g., TAMS) naked He star transferring matter (stably) through the inner Lagrange point to a neutron star. This type of binary has been extensively modeled by Dewi et al. (2002). If confirmed, this would open exciting possibilities for both stellar evolution

studies (see, e.g., Dewi et al. 2002; Justham et al. 2006) and the interpretation of ultraluminous X-ray sources at the lower end of their luminosity function (see, e.g., Colbert & Miller 2004; Fabbiano & White 2006). In the case of CXOU J121538, the peak observed luminosity is only about twice the Eddington limit for accretion of He onto a neutron star. If the accretor in such a system, i.e., with a He donor star, were a stellar-mass black hole, then the Eddington limit would be $\sim 4 \times 10^{39}$ ergs s $^{-1}$; well within the range of ultraluminous X-ray source luminosities.

Finally, we note that CXOU J121538 may be the first known *immediate* progenitor of a compact double neutron star binary; i.e., beyond the second common envelope phase and prior to collapse of the He star core. A perhaps unverifiable prediction is that within some $10^5 - 10^6$ years the evolved core of the He star will collapse to produce a type Ib supernova explosion (see, e.g., Podsiadlowski, Joss, & Hsu 1992; Woosley, Langer, & Weaver 1995) and leave a binary radio pulsar (if the natal kick given to the

pulsar is not so large as to unbind the system; see, e.g., Pfahl et al. 2002 and references therein; Podsiadlowski et al. 2004). The putative neutron star that is currently in the system is in the process of being spun up via accretion torques and will be the rapidly rotating pulsar member of the binary. It is also interesting to note that this predicted event has actually occurred already (given the ~ 10 Myr light travel time for the information to reach us).

We thank Stephen Justham, Philipp Podsiadlowski, Eric Pfahl, and Steve Howell for very helpful discussions. KKG is supported in part by NASA under grant NNG04GC86G issued through the Office of Space Science. DP gratefully acknowledges support provided by NASA through Chandra Postdoctoral Fellowship grant number PF4-50035 awarded by the Chandra X-ray Center, which is operated by the Smithsonian Astrophysical Observatory for NASA under contract NAS8-03060. SR received some support from Chandra Grant TM5-6003X.

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